Benchmark Calculation of the WIMS/RFSP for the Wolsong Nuclear Power Plants 3 & 4 Physics Measurement Data

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For the validation of the WIMS/RFSP code, benchmark calculations were performed using the physics measurement data of the Wolsong nuclear power plants 3 and 4. As was done in the previous study, the benchmark calculations were performed for the criticality, boron worth, reactivity device worth, reactivity coefficient, and flux scan. The results showed that the criticality and boron worth were underestimated by 3~6 mk and ~7%, respectively. The reactivity device worth was generally consistent with the measured data except for the strong absorbers such as the shutoff rods and the mechanical control absorber. The heat transport system temperature coefficient and flux distributions were in good agreement with the measured data.

KEYWORDS: Benchmark, WIMS, RFSP, Criticality, Device worth, Reactivity, Flux

1. Introduction

In the previous study,[1] benchmark calculations were performed for the Canada deuterium uranium (CANDU) reactor physics design and analysis system, consisting of the WIMS-AECL [Ref. 2], SHETAN [Ref. 3] and RFSP [Ref. 4] codes. In that study, the benchmark calculation was done for the Wolsong nuclear power plant (NPP) 2 physics (Phase-B) measurement data and most of the efforts were made to prepare benchmark models of the lattice, reactivity device and reactor core calculations. For the lattice calculation by the WIMS, it was decided to solve the main transport equation in the 89 energy groups with the B1 leakage method and Benoist diffusion coefficient. The reactivity device was modeled for 1/8 of a one lattice bundle by the SHETAN, and the incremental cross sections were generated to be used for the core calculation. The core calculation was performed by the RFSP code using the optimized mesh structure of 44×36×22.[5]

In this study, the benchmark calculations are performed for the Wolsong NPPs 3 and 4 Phase-B test results using the models developed in the previous study.[6] The Phase-B test requires that the prediction of the critical boron concentration matches the measured value within ±0.5 ppm. The allowable errors of the reactivity device worth prediction are relatively large considering the measurement procedure: ±10% for the zone controller unit (ZCU) and ±15% for the adjuster (ADJ), mechanical control absorber (MCA) and shutoff rods (SOR). The allowable error for the neutron flux estimation is 15% in the root-mean-square (RMS).

2. Simulation of Phase-B Tests

The Phase-B test includes the first approach to the criticality and low power tests necessary to verify the physics design and to evaluate the performance of the control and protective systems. Most tests are performed at 0.1% of the full power.

2.1 Criticality Measurement

The critical boron concentrations of the Wolsong NPPs 3 and 4 were 8.93 and 9.34 ppm, respectively. The effective multiplication factors of the core were 0.997 and 0.994, respectively, and therefore the criticality was underestimated by 3 and 6 mk, respectively, which corresponds 0.4 and 0.8 ppm, respectively, in terms of the critical boron concentration.

2.2 Reactivity Device Worth

The reactivity worth of the ZCU was calculated for the initial condition. Since the ZCU was calibrated by the boron concentration change in the moderator, the boron reactivity coefficient was calculated first. The boron reactivity coefficients were 7.66 and 7.70 mk/ppm for Wolsong 3 and 4, respectively. During the physics test, the calibration of the ZCU was performed by dissolving a boron batch in the moderator. After the batch was added, the average ZCU water level was fitted in order to maintain the criticality. The estimated average ZCU level worth is shown in Fig. 1 and compared with the measurement results for typical operating ranges. The maximum error of the ZCU level worth is ~8%.

The reactivity worth of the individual ADJ rod was calculated by the RFSP code. As given in Table 1, the largest difference of the reactivity worth between the calculation and the measurement is ~20%, while the difference of the total ADJ worth is ~2%. The reactivity worth of the ADJ bank was also calculated and the results are given in Table 2.

The reactivity worth of the individual SOR was calculated as shown in Table 3 where the maximum error is ~20%. The individual and bank worth of the MCA were also calculated as given in Tables 4 and 5, respectively. Unlike the case of the ADJ, the reactivity worth of the SOR and MCA were over-predicted by the WIMS/RFSP, which seems to be due to the poor estimation of the thermal neutron flux in the absorber region.

2.3 Reactivity Coefficients

For the heat transport system (HTS) temperature coefficient measurement, the moderator temperature was fixed at 35 ºC and the boron concentration in the moderator was 8.5 ppm. The coolant and fuel temperatures were the same and they were varied from 35 to 260 ºC. The corresponding coolant densities were calculated for D_2O at the saturated and non-boiling conditions with 99.24 and 99.27 wt% purities for Wolsong 3 and 4, respectively. The variation of the HTS temperature coefficient is shown in Fig. 2. The HTS temperature coefficient is generally consistent with the measured data.

For the moderator temperature coefficient (MTC), the coolant and fuel temperatures were fixed at 260 ºC and the boron concentration in the moderator was set at 8.5 ppm. The MTC was calculated by decreasing the temperature from 69 to 35 ºC. The moderator density was calculated for D_2O at the saturated and non-boiling conditions with 99.81 and 99.84 wt% purities for Wolsong 3 and 4, respectively. The reactivity variation temperature is shown in Fig. 3. Compared with the measured data, the simulation error was very large (~50%). It is thought that the error is probably largely dependent on the low boron reactivity worth in the WIMS/RFSP simulation and the inconsistent measurement procedure.

2.4 Flux Distribution

During the Phase-B test, thermal flux scans were performed several times for various reactor configurations. The flux measurement confirms the physics design method and, in particular, the effects of various reactivity devices and the depleted fuel on the neutron flux distributions. The flux scans along a chord of the reactor core were made with fission chamber mapping detectors. Vertical fission chamber scans were performed along 26 vertical flux detector (VFD) assemblies. Horizontal fission chamber scans were carried out along the horizontal flux detector (HFD) tube. The flux scan calculations were performed for the following cases:

(Case 1) Nominal case (with all ADJs),

(Case 2) MCA bank 1 inserted by 50% with ADJs,
(Case 3) MCA all inserted with ADJs,
(Case 4) Without ADJ bank 1, 2, 3 and 4,
(Case 5) Without all ADJs.

The ZCU water level was fixed at 40% and the moderator boron concentration was 8.5 ppm. The flux calculations were performed using the INTREP module of the RFSP code. The flux scan calculations were performed for VFD 19 and HFD 1 for the vertical and horizontal fluxes, respectively. In order to obtain the flux at the detector position, a shape function was generated for the flux variation between the fuel channels. The horizontal and vertical thermal fluxes corrected by the shape function are shown in Figs. 4 and 5, respectively, for Case 1. The RMS errors of the flux calculation are summarized in Table 6, in which the largest error is 10%.

3. Summary and Recommendations

Benchmark calculations of the WIMS/RFSP were performed for the Wolsong NPPs 3 and 4 Phase-B measurement data. The estimation of the reactivity device worth and flux scan were generally consistent with the measured results. However the boron worth and moderator temperature coefficient calculations showed relatively large errors, which could be due to the incremental cross section generation methodology for the reactivity device.

It should be noted that the incremental cross section generation by the WIMS/SHETAN codes didn’t use any adjustment during the homogenization process. However, considering the strong heterogeneity effect of the reactivity device, it would be appropriate to adjust the local lattice parameters to conserve the total absorption rate in the device region. In the future, a super homogenization method will be investigated to improve the performance of the reactivity device modeling in the CANDU core analysis.

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Table 1. Reactivity Worth of the Individual Adjuster Rod

Number	Wolsong-3			Wolsong-4		
	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)
1	0.182	0.218	-16.4	0.178	0.205	-13.2
2	0.590	0.567	4.0	0.583	0.533	9.3
3	0.672	0.692	-2.9	0.671	0.700	-4.1
4	0.348	0.363	-4.0	0.342	0.383	-10.8
5	0.670	0.701	-4.4	0.666	0.711	-6.3
6	0.592	0.547	8.2	0.589	0.574	2.7
7	0.181	0.212	-14.7	0.180	0.229	-21.5
8	0.215	0.279	-22.9	0.209	0.242	-13.5
9	0.744	0.637	16.8	0.743	0.649	14.5
10	0.885	0.888	-0.3	0.882	0.868	1.6
11	0.481	0.515	-6.6	0.475	0.533	-11.0
12	0.886	0.922	-3.9	0.879	0.907	-3.1
13	0.745	0.691	7.9	0.741	0.712	4.1
14	0.214	0.264	-19.0	0.208	0.262	-20.7
15	0.187	0.213	-12.1	0.180	0.207	-12.9
16	0.593	0.512	15.7	0.582	0.511	14.0
17	0.677	0.692	-2.1	0.667	0.686	-2.8
18	0.348	0.373	-6.7	0.341	0.372	-8.4
19	0.676	0.733	-7.8	0.667	0.703	-5.2
20	0.591	0.546	8.2	0.587	0.585	0.4
21	0.183	0.233	-21.4	0.179	0.232	-23.0
Total	10.660	10.880	-2.0	10.549	10.804	-2.4

Table 2. Reactivity Worth of the Adjuster Bank

Number	Wolsong-3			Wolsong-4		
	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)
1	1.175	1.35	-13.0	1.468	1.361	7.9
2	1.509	1.39	8.6	1.751	1.420	23.3
3	1.496	1.34	11.6	1.743	1.431	21.8
4	2.164	1.93	12.1	2.192	1.9 11	14.7
5	1.571	1.87	-16.0	1.600	1.350	18.5
6	1.596	1.80	-11.3	1.602	1.370	17.0
7	2.846	3.31	-14.0	2.082	1.844	12.9
Total	12.357	12.99	-4.9	12.438	10.687	16.4

Table 3. Reactivity Worth of the Individual Shutoff Rod

	Wolsong-3			Wolsong-4		
	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)
1	1.370	1.2 18	12.5	1.364	1.239	10.1
2	1.712	1.592	7.5	1.705	1.586	7.5
3	1.718	1.585	8.4	1.716	1.585	8.3
4	1.362	1.338	1.8	1.352	1.297	4.3
5	1.021	0.890	14.7	1.021	0.918	11.2
6	2.137	1.858	15.0	2.131	1.892	12.7
7	2.136	1.908	12.0	2.132	1.901	12.2
8	1.020	0.973	4.8	1.013	0.969	4.5
9	1.493	1.286	16.1	1.486	1.230	20.8
10	2.663	2.207	20.7	2.654	2.169	22.4
11	2.786	2.329	19.6	2.774	2.303	20.5
12	2.651	2.304	15.0	2.650	2.293	15.6
13	1.497	1.393	7.4	1.487	1.405	5.8
14	1.554	1.297	19.8	1.554	1.282	21.3
15	1.557	1.455	7.0	1.549	1.444	7.3
16	1.488	1.280	16.3	1.488	1.230	21.0
17	2.661	2.173	22.5	2.643	2.145	23.2
18	2.790	2.338	19.4	2.775	2.302	20.6
19	2.660	2.295	15.9	2.651	2.276	16.5
20	1.487	1.392	6.8	1.494	1.388	7.6
21	1.025	0.896	14.4	1.017	0.880	15.5
22	2.143	1.873	14.5	2.139	1.793	19.3
23	2.134	1.934	10.3	2.129	1.880	13.3
24	1.012	0.969	4.4	1.009	0.959	5.2
25	1.372	1.213	13.1	1.372	1.227	11. 8
26	1.707	1.601	6.6	1.712	1.536	11.5
27	1.712	1.619	5.8	1.703	1.583	7.6
28	1.361	1.343	1.4	1.362	1.309	4.1
Total	50.229	45.378	10.7	50.082	45.378	10.4

Table 4. Reactivity Worth of the Individual Mechanical Control Absorber

	Wolsong-3			Wolsong-4		
	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)
1	2.14	1.920	11.5	2.138	1.762	21.3
2	2.15	1.999	7.6	2.137	1.902	12.4
3	2.18	1.814	20.0	2.166	1.771	22.3
4	2.17	2.001	8.4	2.156	1.901	13.4
	8.637	7.734	11.7	50.082	45.378	10.4

Table 5. Reactivity Worth of the Mechanical Control Absorber Bank

	Wolsong-3			Wolsong-4		
	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)	WIMS/RFSP (mk)	Phase-B (mk)	Error (%)
1	5.843	3.455	69.1	5.801	4.686	23.8
2	25.843	5.042	15.9	5.802	4.595	26.3
Total	11.686	9.580	22.0	11.603	9.580	21.1

Table 6. Root Mean Square Error of the Flux Distribution

RMS Error (%)		CASE 1	CASE2	CASE3	CASE4	CASE5
Wolsong-3	Vertical	7.4	1.6	1.0	4.8	4.1
	Horizontal	7.2	6.4	9.9	4.4	7.0
Wolsong-4	Vertical	3.3	7.7	11.2	6.5	6.3
	Horizontal	5.0	4.7	6.3	5.5	2.8

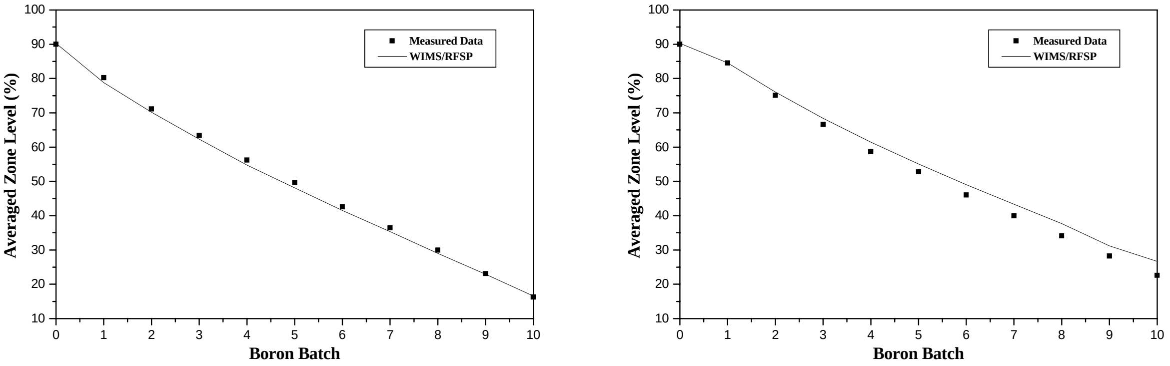

Fig. 1 Calibration of the ZCU worth for the Wolsong NPPs 3 & 4

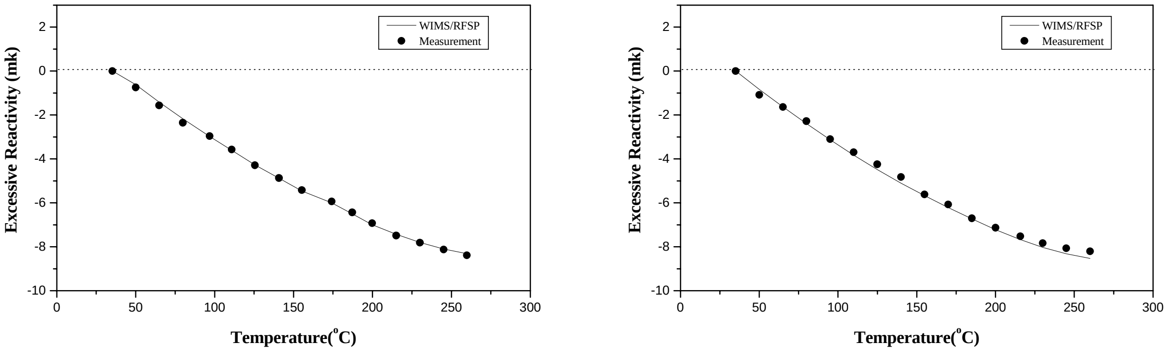

Fig. 2 Heat Transport System Temperature Effect for the Wolsong NPPs 3 & 4

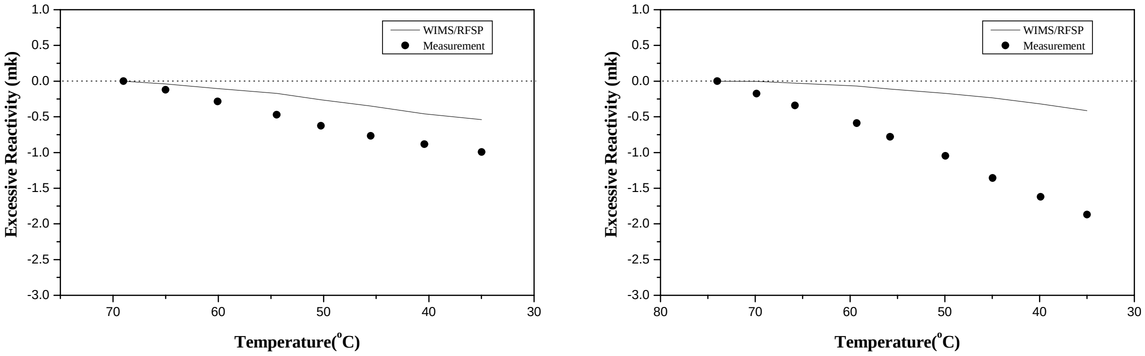

Fig. 3 Moderator Temperature Effect for the Wolsong NPPs 3 & 4

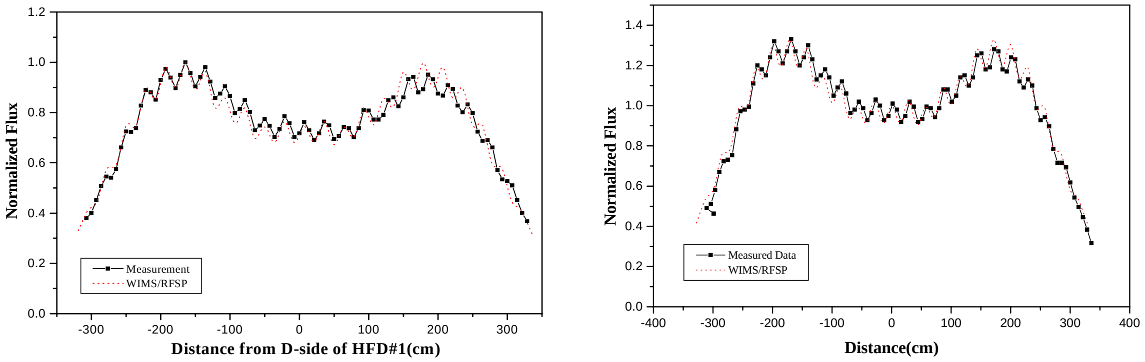

Fig. 4 Horizontal flux Scan for the Wolsong NPPs 3 & 4

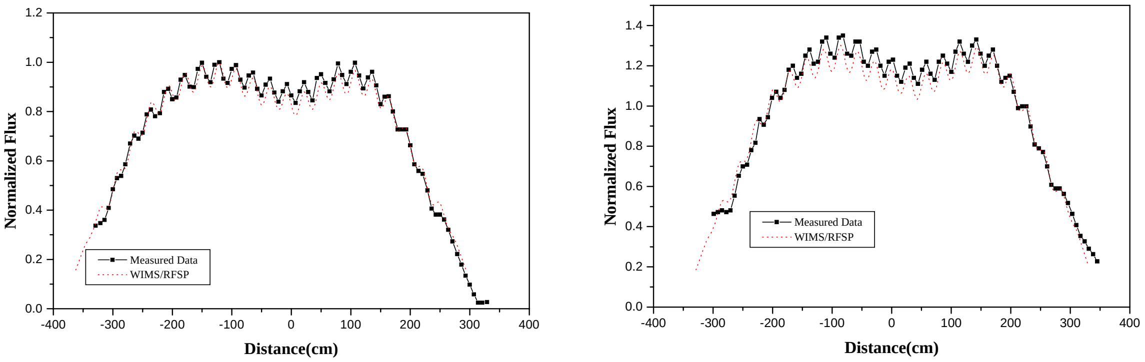

Fig. 5 Vertical flux Scan for the Wolsong NPPs 3 & 4